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RESEARCH ARTICLE

Modelling and calculating the harmonic penetration of the high power traction using the double domain simulation method

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Abstract

The paper presents the results of a long term research work. The authors are modelling the penetration and elimination of harmonic disturbance originating from the high power railways.

This kind of problem is usually handled using time domain or frequency domain simulation. As it is well known, the modelling of harmonic sources is more accurate in time domain simulation, while the frequency dependence of the passive network is more accurate in frequency domain. That is why a novel method was developed named double domain simulation method, which is a combination of frequency and time dependent models. To calculate the sophisticated model of the electric locomotive as a non-linear load a time dependent model must be used. The traction supply system together with the equivalent supply network impedance could be calculated accurately in frequency domain. An iteration algorithm is developed converting the variables in every iteration step between the time and frequency domain.

The application of the double domain simulation method to solve the harmonic filtering of high power railway system is introduced. The results prove that the method is suitable for studying the effect of different filtering methods, like the passive, active and hybrid filtering.

Keywords

power quality · harmonics · computer simulation · traction supply systems · hybrid filtering

Acknowledgement

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1 Introduction

The electric railway is in competition with other possibilities of transportation. The locomotives became faster and faster and in consequence their power is growing as well. The high power locomotives pollute the supply system with harmonics. In order to ensure the voltage quality of the whole energy system, it is necessary to reduce this pollution.

Strict requirements were established on the voltage quality of the electric supply network in the last decade. One of these requirements is in connection with the harmonic distortion of the voltage [1]. The voltage distortion is caused by the non-linear loads connected to the network on different voltage levels. This distortion could cause problems both in the high power energy system and the parallel telecommunication lines (psophometric noise) [3].

After the spreading of locomotives equipped with DC traction motors and rectifier units the disturbance originating from railway traction systems has increased. Harmonic filters are used to limit the harmonic currents flowing into the upstream network and to decrease the resonance effect causing current amplification along the 25 kV supply line. Reducing the harmonic currents decreases the psophometric current and voltage as well.

More kind of simulation models has been investigated calculating the harmonic effect of the electric traction. In a former paper [2] a detailed model of the traction system was discussed in the frequency domain. A new high computational efficiency model has been presented for an Italian configuration [10]. Both time and frequency domain models have been used for the DC traction network representation and a double-iterative procedure was used calculating the locomotive current.

In this paper a novel calculation method is discussed for the Hungarian 25 kV AC traction supply network. In the following sections the modelling possibilities of the harmonic effect in this kind of railway networks are presented, the detailed introduction of the traction system elements, the passive, active and hybrid filtering methods are reported. Finally some calculation results (harmonic currents and voltages, calculated psophometric values) are published. For those readers who are not specialists in the topic of power quality issues, a short theoretic overview is presented in the Appendix chapters about the harmonics, the psophometric interference and the harmonic filtering.

2 Modelling procedures

To decide what kind of harmonic filter should be used it is possible to investigate more kinds of models.

2.1 Simplified model

The easiest way is the simplified model, where the whole model is in the frequency domain. In this case it is necessary to determine the locomotive current spectrum in advance by site measurements or other calculations (e. g. it is possible to use a statistical computation based on site measurements [11]).

Regarding the harmonic simulation in frequency domain the locomotive is considered as a harmonic current generator on the frequencies measured in the spectrum.

2.2 Transient model

It is possible to compose a sophisticated model working in the time domain. The parameters of the locomotive can be calculated without any difficulties in time domain, but the elements of the network are known in the frequency domain as results of site measurements.

The biggest problem is with the upstream network, because it can be calculated just with its driving point impedance. This impedance curve is frequency dependent and the conversion could result in a transfer function with at least 5-6 poles and zeros. The most difficult problem is the simulation of the frequency dependent damping.

2.3 Double domain simulation

Our goal is the combination of the two domains: the time domain calculations have been reduced to the locomotive, and the whole network is calculated in the frequency domain. The procedure is detailed in Chapter 4.

3 Modelling the electric traction's supply [4]

The electric railway system is consisting of four main components (Fig. 1a) [2]:

- the locomotives
- the contact line system
- the feeding transformer
- the high voltage supply network

3.1 Locomotives

The locomotives are running under the contact line system, dividing it into two parts. At the contact point the locos could be represented by a base frequency consumer and harmonic generator. After studying the modelled engines [6] the following conclusions can be drawn [2]:

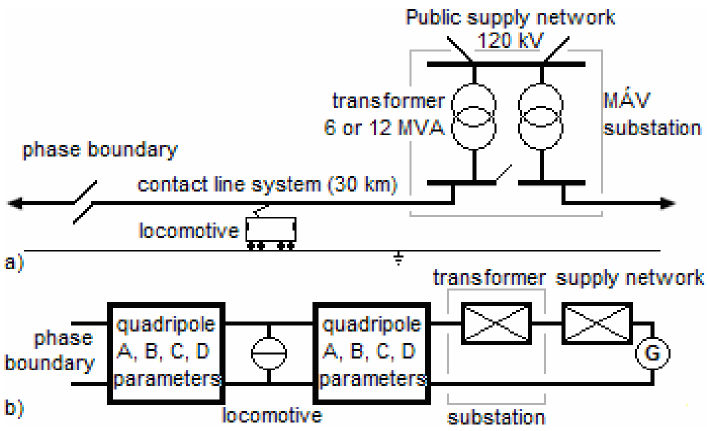

Fig. 1. Simplified circuit for calculation of harmonic effect a) general traction-current feeding arrangement b) circuit representation of the traction supply system

- In case of odd harmonics, the harmonic components significantly decrease if the order increases.
- Even harmonics are significantly smaller than the neighbouring odd harmonics.
- From the site measurements of [2] it may be concluded that the magnitude of the current harmonics injected by the locomotives are practically independent of the network configuration of the traction system and the location of the engine.

Thus the locomotive can be considered as a current generator with the odd harmonics. The common block diagram of the Hungarian locomotives equipped with DC traction motors can be seen on Fig. 2.

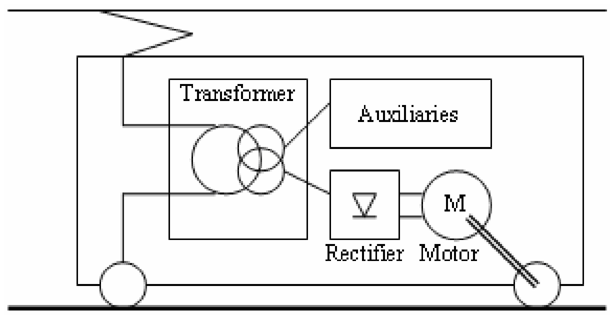

Fig. 2. Simplified block diagram of the Hungarian locomotives

3.2 Contact line system

The contact line system should be considered as a multiconductor system with earth return that is composed of the contact wire(s), suspension wire(s), and the return rails. The length of the system is an average of 30 km, where the feeding transformer is connected to one of the ends. The phase boundary is at the other end that separates this section from the next section.

The contact line system can be reduced to a two-wire-system that leads the current. The reduction has to be performed on every harmonic. The contact line system can be considered as a quadripole (occasionally divided into two parts by the locomotive) that is terminated by the driving point impedance at the substation when the far end is open. The parameters are based on reference [2].

3.3 Feeding transformer

The feeding transformer could also be considered as a quadripole which consists of the magnetizing and the leakage reactance. The establishment of reference [2] shows that the magnetizing impedance can be neglected, so it is enough to calculate every frequency with the leakage impedance. The parameters could be calculated by an expression stated by reference [2].

Usually, there are two transformers in a substation and each of them feeds geographically two different directions. Because the two transformers are connected to separate busbars the two traction sections can be treated independently. Only if one of the transformers is under maintenance are the traction sections interconnected, but it is an emergency condition. That is why we do not calculate with these cases in the model, although it would not mean theoretical difference.

3.4 High voltage supply network

The driving point impedance as seen from the 25kV side is equal to the sum of the positive and negative sequence impedances of the high voltage supply network. Therefore it is necessary to measure the driving point impedance in every substation included in the model. The impedance-frequency functions that are determined by the measured impedances could be used with a kind of approximate method [2].

4 The double domain simulation

The traction supply system model contains elements shown in Fig. 1.b. This model is calculated in the frequency domain, because all the necessary parameters are given in the frequency domain as results of laboratory and site measurements [4].

To calculate the sophisticated model of the electric locomotive as a non-linear load a time dependent model must be used. It determines the current spectrum of the engine in function of the distorted supply voltage. Because the voltage distortion is caused by the loco itself, an iteration algorithm was developed to convert the variables between the time and frequency domain vice and versa. This procedure is followed until the difference of the calculated harmonic voltages of any order of two consecutive steps gets low enough. The test calculations with one or two locomotives and 1 % tolerance needed no more than 8 iterations. This method is called double domain simulation; its flowchart can be studied on Fig. 3 [4].

5 Calculation results

For studying low frequency disturbances, the harmonic orders must be examined till the 50th harmonic according to the norm EN50160 [1], [3]. In this paper the calculations are made with V63 locomotives, the traction system is 30 km long, the engine is 10 km far from the substation. The detailed analysis

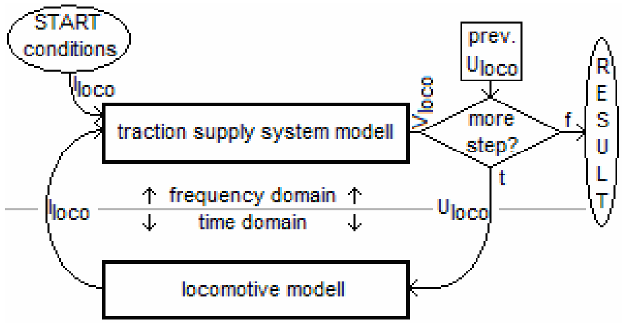

Fig. 3. Double domain simulation method

of the traction supply system and the double domain simulation method was published in [4], the applied V63 locomotive model is published in [6]. The resultant current and voltage spectrum and time functions are detailed in the following subchapters, the THD and psophometric values are collected into Table 1, 2 and Table 3 in Chapter 5.7.

5.1 Simulation results without harmonic filtering

The unfiltered current and voltage spectrums and time functions can be studied on Figs. 4 and 5. In this case a high current distortion could be observed. The locomotive is equipped with DC traction motor and AC/DC converter (semi-controlled bridges of thyristors and diodes), this is the origin of the injection of the harmonic currents. The 1. different columns show the loco current spectrum and the 2. different the current at the substation. Comparing these two functions the current amplification can be calculated, which was discussed in details in [4].

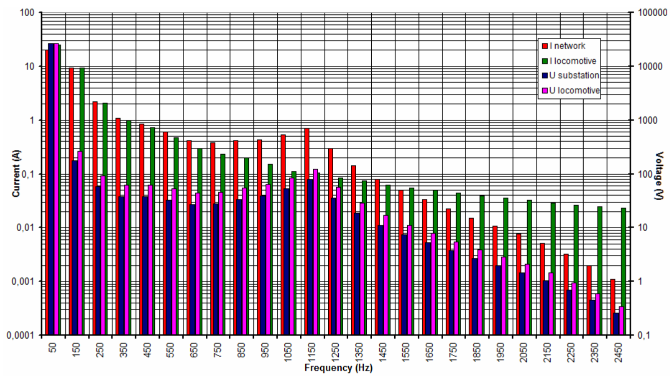

Fig. 4. Spectrums without filtering

For the following calculations it is necessary to set the filter to eliminate the 3^{rd} and 5^{th} orders, as the highest magnitude harmonics, and it is possible to plan a broadband filter for the higher harmonic orders. Because of the broadband filter – which is developed to decrease mostly the 21^{st}-25^{th} orders – would amplify the 7^{th} harmonic, it is necessary to set a filter to the 7^{th}, too [2].

5.2 Passive filtering

In the next case a passive filter was installed to the substation. Series RLC circuits were tuned to the 3^{rd}, 5^{th} and 7^{th} harmonic orders, and a broadband filter was set to reduce all the harmonic

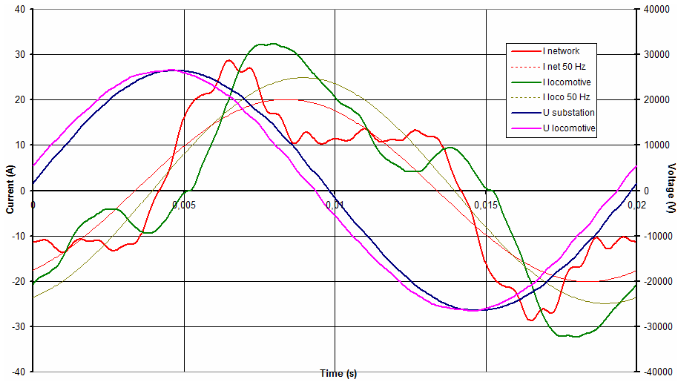

Fig. 5. Time functions without filtering

orders above (Fig. 6). Using passive filters it is necessary to calculate the reactive power balance, that is why for this calculation the reactive power of the filter was set to 400 kvar. There are two railway substations in Hungary where this kind of passive filter is installed, the reactive power can be set between 0.4-2 Mvar with 0.3-0.4 Mvar steps [2]. The calculated spectrums can be studied on Fig. 7, the time functions on Fig. 8.

One can conclude, that the effectiveness of the filter is acceptable, the THD value of the current flowing into the HV network is under 10 %, the voltage THD is low enough, so they comply with the standards.

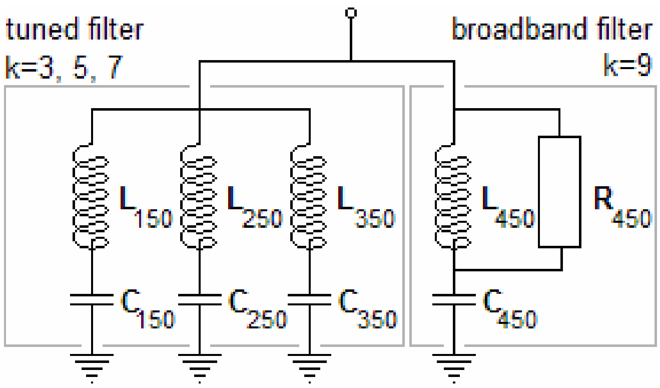

Fig. 6. Passive filter set

5.3 Active filtering

In this case an active filter was set to the 3^{rd}, 5^{th} and 7^{th} harmonic orders. The switching frequency was set to 10 kHz, for further information see Fig. 9 and [7].

5.4 Hybrid filtering with 600 kvar reactive power

For much better results it is possible to apply a broadband passive filter of 600 kvar reactive power. This is the maximum reactive power filter capacity installed in substations mentioned in Chapter 5.2. In some cases the broadband filter can cause overcompensation in the substation. Besides the harmonic filtering, the active filter can control the reactive power balance. The calculation results can be studied on Figs. 16 and 17.

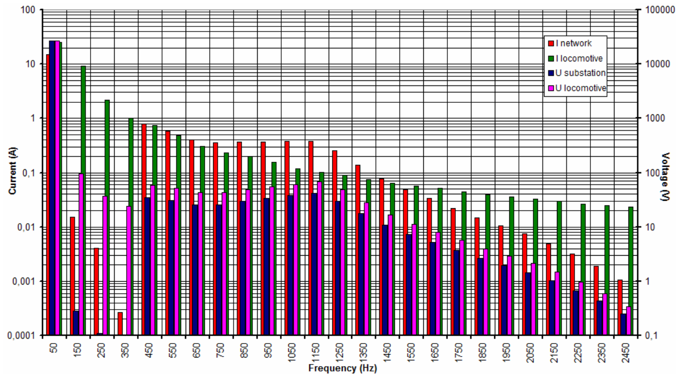

Fig. 7. Spectrums with passive filtering

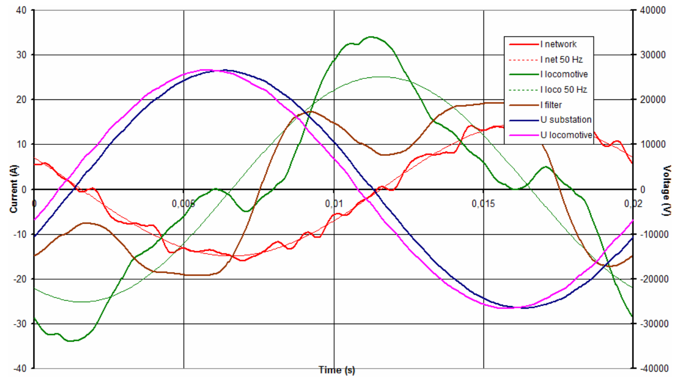

Fig. 8. Time functions with passive filtering

5.5 THD and psophometric values

Table 1 and 2 provide the THD and Table 3 the psophometric values after the previous four calculations.

In the calculation of Chapters 5.2, 5.5 and 5.6 the reactive power compensation is discussed together with the harmonic filtering. By these conditions there is a significant difference in the amplitude of the fundamental frequency current component, to give a correct comparison of the current THD values they are presented in Amperes in Table 1. In addition the fundamental frequency current components are presented. In Table 2 the current THDs together with the substation and locomotive voltage THD values are presented in %.

From Table 1 it is possible to conclude that each of three filtering methods discussed fit the criteria, namely the THD of the network current should not exceed 10 %.

The calculation results are presented on Figs. 10 and 11. It is possible to conclude that altough the highest 21^{st} and 23^{rd} harmonics has not been filtered, the THD value of the current is less than it was in the previous case. Regarding the psophometric values this type of filtering is not really effective, because:

- the current components of higher frequencies (800-1000 Hz) are not filtered,
- the active filter gives only a current injection at the substation, it does not affect the resultant impedance of the network. It means that this active filter can not reduce the parallel resonance impedance of the network.

It is worth mentioning, that this solution has no affect on the fundamental frequency reactive power balance, it means that according to the Hungarian tariff system the consumer should pay for reactive power as well.

5.6 Active filtering with additional $21^{st} - 23^{rd}$ *harmonic current injection*

In [9] a theoretical ideal active filter was discussed. With this filter the higher order harmonics could be filtered. It is possible to extend the active filter of the previous calculation with that ideal filter reducing the 21^{st} and 23^{rd} harmonics, as the highest amplified current components. The results of calculation can be studied on Figs. 12 and 13.

In this case the 21^{st} and 23^{rd} harmonic currents are totally filtered and the THD and psophometric values have reduced effectively.

5.7 Hybrid filtering

In this case the filtering of Chapter 8.3 is extended with a broadband passive filter of 300 kvar reactive power. The calculation results are given on Fig. 14 and on Fig. 15. This case results in almost pure sinusoidal HV network current time function and the psophometric values along the supply line are 35 % lower than those of the unfiltered calculation.

Tab. 1. Fundamental frequency current components and THD current values in Amperes by different filtering methods

	$I_{1network}$	$I_{1tract.s.}$	$I_{network}$	$I_{tractions.}$	I_{loco}
Unfiltered	20.12 A	20.12 A	9.88 A	9.88 A	9.62 A
Passive	14.87 A	20.36 A	1.37 A	9.72 A	9.59 A
Active	19.62 A	19.85 A	1.66 A	9.65 A	9.50 A
Active w. ideal	19.63 A	19.88 A	1.39 A	9.61 A	9.50 A
Hybrid	14.14 A	20.22 A	1.39 A	9.67 A	9.56 A
Hybrid w. 600k	14.21 A	20.26 A	1.29 A	9.66 A	9.57 A

Tab. 2. THD values in % by different filtering methods

	$I_{network}$	$I_{tractions.}$	I_{loco}	$U_{subst.}$	U_{loco}
Unfiltered	49.10 %	49.10 %	38.62 %	0.88 %	1.35 %
Passive	9.22 %	53.85 %	38.17 %	0.38 %	0.74 %
Active	8.44 %	48.64 %	38.61 %	0.50 %	0.90 %
Active w. ideal	7.10 %	48.35 %	38.54 %	0.35 %	0.69 %
Hybrid	9.88 %	47.82 %	38.28 %	0.33 %	0.65 %
Hybrid w. 600k	9.07 %	47.70 %	38.24 %	0.27 %	0.58 %

In Table 3 the psophometric values can be studied. According to the results, the best values can be ensured with the hybrid filter. Comparing this case with the unfiltered one, the psophometric voltage could be reduced by 30-40 % along the whole supply line. The reduction of the HV network current is significant, too.

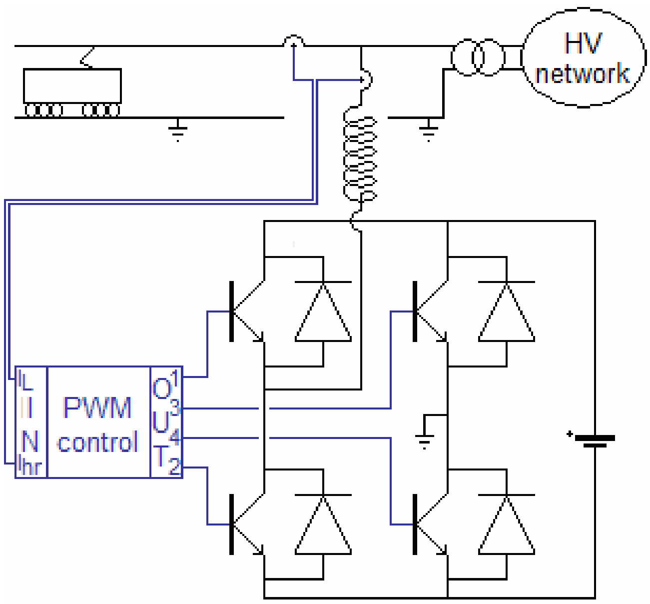

Fig. 9. Active filter

Tab. 3. Psophometric currents and voltages by different filtering methods

	$I_{network}$	$I_{tractions.}$	I_{loco}	$U_{subst.}$	U_{loco}
Unfiltered	1.54 A	1.54 A	0.95 A	126.05 V	200.13 V
Passive	1.14 A	1.36 A	0.97 A	93.60 V	151.94 V
Active	1.43 A	1.54 A	0.96 A	125.77 V	199.96 V
Active w. ideal	1.12 A	1.29 A	0.96 A	84.70 V	135.70 V
Hybrid	1.08 A	1.22 A	0.96 A	76.62 V	119.45 V
Hybrid w. 600k	0.95 A	1.14 A	0.97 A	61.32 V	94.48 V

6 Conclusion

In Chapter 5 different filtering possibilities were discussed. The effectiveness of all kinds of filters is significant, however, the active filter has practically no effect on the psophometric values along the supply line.

The hybrid filter provides the advantages of both passive and active filtering. It could be also suitable for the newer type of locomotives, some of them started working in Hungary during the last years. The goal of the paper was to prove the usefulness of the application of the double domain simulation method. The simulation was made with the parameters of locomotive V63 series, having the highest power and generating the highest distortion factor in Hungary in order to investigate the difference between the possible filtering methods.

As a conclusion the double domain simulation is a suitable and accurate method for solving all kinds of problems, where processes in time and frequency domain should calculate simultaneously as in case of harmonic filtering design. In the paper the application of double domain simulation method helped to select the most advantageous solution, regarding the composition of reactive power compensation and harmonic filtering.

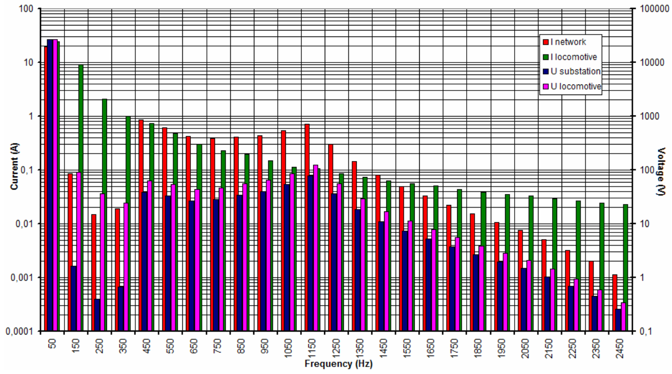

Fig. 10. Spectrums with active filtering

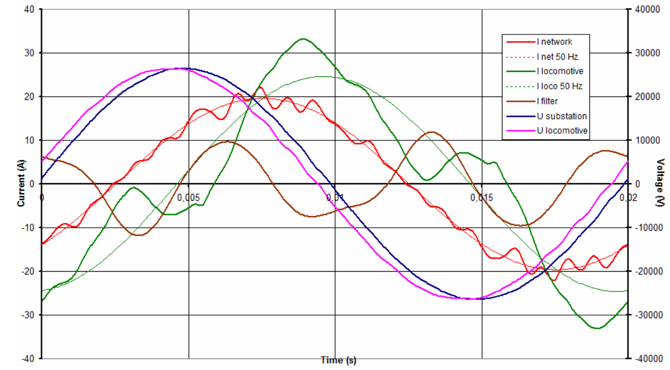

Fig. 11. Time functions with active filtering

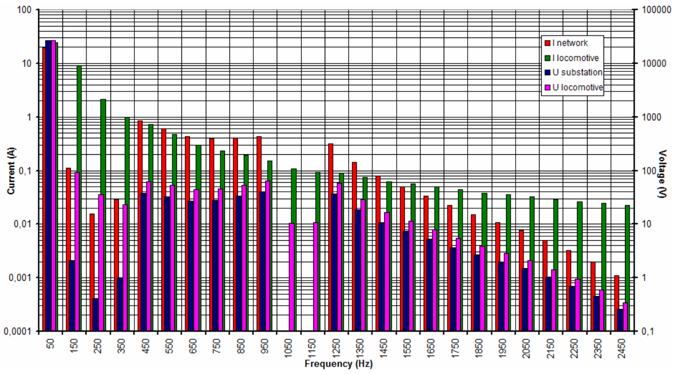

Fig. 12. Spectrums with active filtering (ideal 21^{st}-23^{rd} filter included)

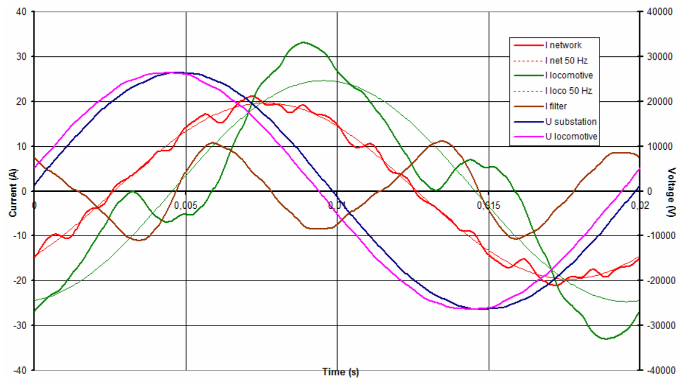

Fig. 13. Time functions with active filtering (ideal 21^{st}-23^{rd} filter included)

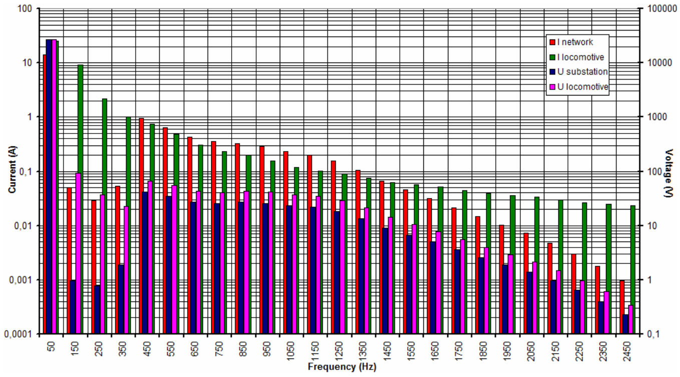

Fig. 14. Spectrums with hybrid filtering

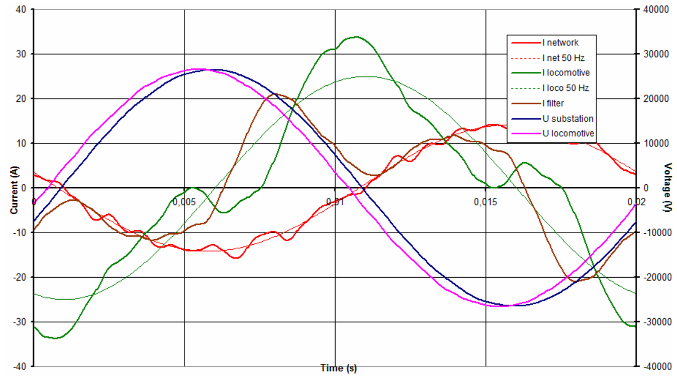

Fig. 15. Time functions with hybrid filtering

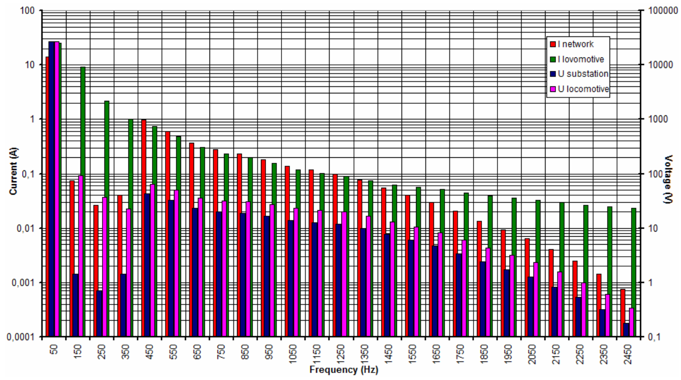

Fig. 16. Spectrums with hybrid filtering (with 600 kvar reactive power)

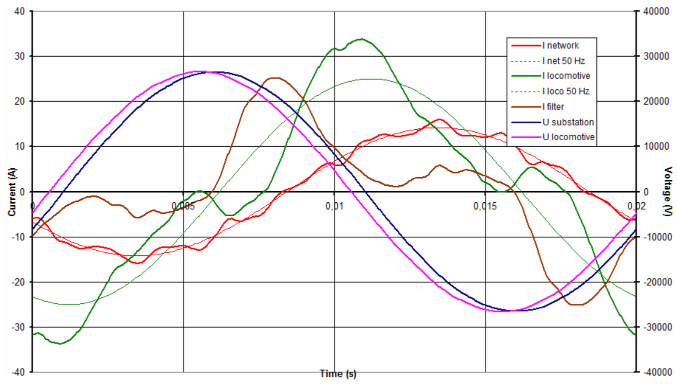

Fig. 17. Time functions with hybrid filtering (with 600 kvar reactive power)

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Appendix

A-1. Effects of harmonics

The locomotive can be considered as a fundamental frequency consumer and a harmonic current source. The harmonic components of current could cause the following problems [2]:

- resonance effect with overvoltage and overcurrent consequences,
- additional losses,
- psophomentic disturbance of the telecommunication systems,
- disturbance in the remote control systems,
- malfunction of protection devices,
- misoperation of semiconductor-controllers.

The harmonic disturbance basically could be characterized by the total harmonic distortion factors:

$$THD_x = \sqrt{\sum_{k=2}^{\infty} X_k^2} \tag{1}$$

$$THD_x^{\%} = \frac{\sqrt{\sum_{k=2}^{\infty} X_k^2}}{X_1} \tag{2}$$

where

$k = \frac{f}{50\,Hz}$: the harmonic order,
X_k : k-th harmonic component of I or U
X_1 : fundamental frequency component of I or U. [3]

A-2. Psophometric interference

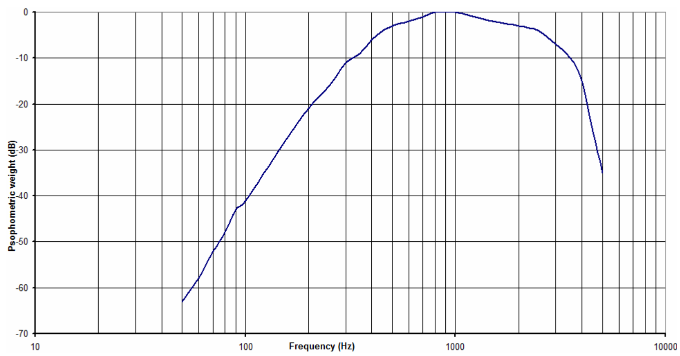

Fig. 18. The psophometric weight

The high power lines could influence the neighbouring telecommunication networks by the following ways:

- capacitive coupling: the voltage of the power line causes charging current
- inductive coupling: the line current induces longitudinal emf.

The most dominant part of the psophometric noise is the inducing effect caused by the zero sequence components of the current. The power balance of the three-phase is near symmetrical during normal operation, that is why the coupling is measurable only if the distance between the two systems is comparable with the phase distance of one system. However, the electric traction is a single-phase system with earth return and in consequence it is a natural zero sequence system. That is why it is important to calculate the psophometric noise [2].

By telecommunication lines the rate of the disturbance could be characterized by the so called psophometric voltage. It could be calculated by this formula:

$$U_p = \sqrt{\sum_f \left(\frac{p_f}{p_{800}} \cdot U_f \right)^2} \tag{3}$$

where

U_f : voltage component by f frequency,

p_f : psophometric weight by f frequency,

$p_{800} = 1000$.

The psophometric weight has been determined after human tests; it could be seen on Fig. 18. It could be concluded, that the main part of the noise disturbance is caused by the 800 Hz and surrounding harmonics. The psophometric weighting could be applied for the current components too, the formula is the same like in (A-3), however, this value is characteristic to the zero sequence current of power line regarding its possible disturbing effect. This is the so called disturbing current [2].

A-3. Harmonic filtering

Harmonic filters are used to limit the harmonic currents flowing into the upstream network and to decrease the resonance effect causing current amplification along the 25 kV supply line. The filter could be located on the loco itself or at the substation. Because of the different type of locos running simultaneously on the same traction section the most effective place for the harmonic filter location is the 25 kV side of the substation. Basically there are two kinds of filters: passive and active filters and it is possible to combine them, these are called hybrid filters.

A-3.1 Passive filtering

The passive harmonic filter is a set of series resonance circuits tuned to the frequencies to be filtered and connected parallel with the non-linear load. The passive harmonic filter has low impedance on its tuned frequency, that is why it shunts the network for the current of the tuned harmonic order [2].

The series tuned RLC circuits are used to reduce the harmonic component of the current flowin into the supply network on the tuned frequency (Fig. 19a), the broadband filters (Fig. 19b) have wide bandwidth reducing more orders.

Harmonic filtering is often linked with the problem of fundamental frequency reactive power balance. The passive filter is used to compensate the inductive reactive power as well, because it shows capacitive reactance on the fundamental frequency [2].

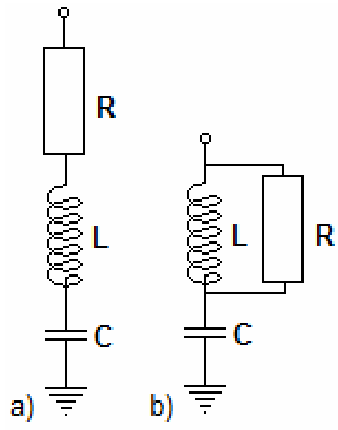

Fig. 19. Basic types of passive filters
a. series tuned RLC b. broadband filter

A-3.2 Active filtering

The active harmonic filtering (Fig. 20) is an electronic method to convert the basically non-sinusoidal current of the consumer into sinusoidal one regarding the resultant supply side network current. The active filters are controlled current generators controlled by microprocessors or microcontrollers, injecting the reciprocal value of selected frequency components to the network [3] [7].

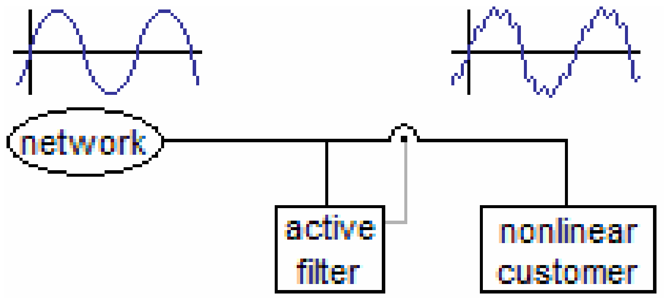

Fig. 20. Active filtering

A-3.3 Hybrid filtering

If it is necessary to filter more harmonics together, it is possible to combine the two previous methods, to compose a hybrid filter. Usually the lower orders – which have bigger power – are eliminated with active filters. Because of the limitation of the switching frequency of the valves (GTOs or IGBTs) for higher harmonics the effectiveness of the active filters are not so high, that is why it is possible to filter them with a broadband passive filter.

It is possible to apply the hybrid filtering method without any capacitive current injection. The new locomotives can work with power factor of 1, thus they do not need any reactive power compensation.